SAGEBRUSH SOUNDSCAPES AND THE EFFECTS OF GAS-FIELD SOUNDS ON GREATER SAGE-GROUSE

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ABSTRACT: Greater Sage-Grouse (*Centrocercus urophasianus*) use elaborate acoustic and visual displays to attract and select mates, and females and chicks depend on acoustic communication during brood rearing. A potential threat to the grouse is sounds associated with human activity. During April, 2013–2020, we collected 17,825 hours of acoustic data in three different acoustic situations in the sagebrush of Wyoming: rural, undeveloped areas (6), at Greater Sage-Grouse leks in a natural-gas field (20), and near active machinery in that gas field (17). The average existing sound levels in undeveloped sagebrush areas were L_{Aeq} = 26 dB and L_{A50} = 20 dB, and the average background sound level was L_{A90} = 14 dB. These values are lower than previously reported, due in part to our use of more sensitive equipment as well as addressing the influence of the instruments' electronic self-noise. L_{Aeq} and L_{A50} at leks in the gas field ranged from 25.5 to 33.7 dB and 20.5 to 31.3 dB, respectively, depending on the distance, number, and type of nearby activities. Sound levels at leks were correlated with trends in the number of grouse using the lek: the higher the sound level, the greater the likelihood of a decline. Thresholds above which declines occurred were L_{Aeq} = 31 dB and L_{A50} = 26 dB. Leks with L_{Aeq} > 31 dB and L_{A50} >26 dB, 100% and 91%, respectively, had declining trends. Our findings suggest that the current policy of limiting sound levels at leks to L_{A50} < 10 dB (or L_{Aeq} < 15 dB) over the background sound level is appropriate, if an accurate background level is used.

Populations of Greater Sage-Grouse (*Centrocercus urophasianus*) have declined dramatically because of habitat loss, degradation, and fragmentation resulting from human activity such as fuel extraction, urban development, traffic on roads, and installation of power lines. Further adverse factors are improper management of grazing, altered fire regimes, and invasion by non-native annual plants (Connelly et al. 2004, Aldridge et al. 2008, Naugle et al. 2011, Boyd et al. 2014, Coates et al. 2016). Several studies have suggested that disturbance from noise pollution may be one causal mechanism by which human activities depress sage-grouse populations, on the basis of observations that attendance at leks in noisier areas is often lower (Rogers 1964, Braun et al. 2002, Connelly et al. 2004, Holloran 2005, Holloran and Anderson 2005, Connelly et al. 2011). Studies confirmed this effect experimentally by introducing sounds recorded at operating natural-gas fields to otherwise undisturbed leks and finding immediate and sustained declines in lek attendance by comparison to paired control leks, as well as increased stress hormones and altered behaviors (Blickley and Patricelli 2012, Blickley et al. 2012). However, because of the limited number of leks at which the sounds were played experimentally, this approach was not able to determine the threshold level at which sounds from natural-gas development affect the sage-grouse. Previous research on songbirds suggests the possibility of a nonlinear threshold response to anthropogenic sound, with effects beginning when the sound is 10 dB or more above background levels (WGFD 2003, Dooling and Popper 2007). Based on this research, current management strategies for Greater Sage-Grouse in many states limit anthropogenic sound at known leks to 10 dBA above background levels. Nevertheless, we do not yet know if this threshold is appropriate for the Greater Sage-Grouse, and there is little agreement on the measures of sound appropriate for use in calculations of allowable levels (Blickley and Patricelli 2012, Patricelli et al. 2013).

The Bureau of Land Management's Record of Decision (BLM 2008) for the development of a gas field in the Pinedale Anticline project area south of Pinedale, Wyoming, included a matrix that listed species of concern and factors needing monitoring for them. The Greater Sage-Grouse was one of those species, and noise was identified as a factor to be monitored.

Therefore, we identified four primary objectives of this study. (1) To determine sound levels and sound sources during the spring lekking period in rural sagebrush (*Artemisia* sp.) habitats in Wyoming that support the grouse and are away from gas fields. (2) To determine levels of sound generated by common activities in the Pinedale gas field. (3) To measure sound levels at Greater Sage-Grouse leks in this gas field. And (4) to assess the relationships between sound levels at leks in and near the gas field and changes in counts of male sage-grouse at those leks.

State agencies commonly use counts of males at sage-grouse leks as a measure of local abundance and trends in attendance over time (Reese and Bowyer 2007, Doherty et al. 2010). We examined the relationship between lek-attendance trends and sound levels at leks, and we make specific recommendations for the measurement, assessment, and management of anthropogenic sounds relative to the Greater Sage-Grouse.

METHODS

Study Area

In 2000, the state of Wyoming established local working groups to develop and implement conservation plans in eight regions for the benefit of the Greater Sage-Grouse and its habitats (WGFD 2003; Figure 1). These areas were selected on the basis of sagebrush habitat and known populations of the grouse. We measured sound levels in four of these areas: Bates Hole/Shirley Basin, Bighorn Basin, Upper Green River Basin, and Wind River/Sweetwater River Basin. The Pinedale gas field lies in the Upper Green River Basin and has been developed extensively for gas extraction. Its elevation ranges from 2073 m to 2286 m, and precipitation averages 30 cm annually (Western Regional Climate Center, Reno, Nevada). The vegetation is primarily big sagebrush (*Artemisia tridentata*), native perennial grasses such as needle and thread (*Hesperostipa comata*), thickspike wheatgrass (*Elymus lanceolatus*), Indian ricegrass (*Achnatherum hymenoides*), and bluebunch wheatgrass (*Pseudoroegneria spicata*), and forbs such as hoary tansyaster (*Machaeranthera canescens*), buckwheat (*Eriogonum* spp.), fleabane (*Erigeron* spp.), and phlox (*Phlox* spp.).

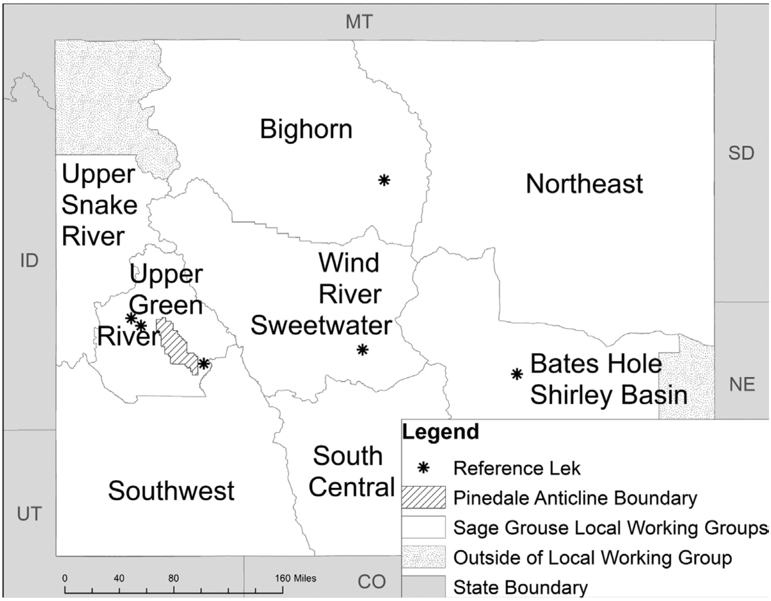

Figure 1. The eight areas of Wyoming defined as local sage-grouse working groups (WGFD 2003), with six undeveloped locations for reference measurement of sound levels (asterisks). Diagonal shading, the Pinedale Anticline project area, in the Upper Green River Basin area, just south of Pinedale.

Definitions

Two sound-level metrics important in this study are the *background sound level* and the *existing sound level*. The *background sound level* is the level in a given environment without contributions from the source of interest (ANSI 1988, 1994). The background sound level (also often referred to as "baseline" or "residual") is calculated as the metric L_{A90}, the level exceeded 90% of the time, or the level beneath which the quietest 10% of measurements lie (EPA 1971, ANSI 1988, BSI 2019; the "A" in L_{A90} means the level is A-weighted, see definition below). L_{A90} is generally effective at discounting intermittent anthropogenic sounds; however, background sound levels are often difficult to measure accurately because of interference by such sounds. If this interference prevents accurate measurement of background sound levels, and the responsible activities cannot be shut down, the measurements should be made in a similar habitat without any such activity (ANSI 1994). L_{A90}, when measured in the presence of the source of interest, is not an accurate representation of background sound level, especially when human activities generate continuous or near-continuous sound. In most rural situations where anthropogenic sounds are uncommon, L_{A90} is usually effective at excluding those sources. The term "background sound level" is preferred over "baseline sound level" because "baseline" is used in the environmental review process of the National

Environmental Policy Act to mean "current conditions," and, in acoustic metrics, "current conditions" means "existing sound level."

The metrics L_{A50} and L_{Aeq} are both used to describe the *existing sound level*, which is the level of all sounds in a given area, including all natural and non-natural sound sources (ANSI 1988, 1994). L_{A50} represents the sound level exceeded 50% of the time, or the median of all measurements (EPA 1971). It is often used to quantify the existing sound level, in part, because it is not influenced by short, loud sounds (as L_{Aeq} is) and is often the best representation of "typical" sound levels at a location. L_{Aeq} is the "equivalent sound level," which is a logarithmic average (i.e., on an energy basis) of sound-pressure levels over a specific interval. L_{Aeq} is useful because it does include short but loud noises, which L_{A50} might miss, and such events could be important to wildlife. Both metrics are often used in characterizing levels of anthropogenic sounds relative to their potential effects on wildlife (Pater et al. 2009, Barber et al. 2011, Patricelli et al. 2013), and L_{A50} is specified in some management documents (in Wyoming, Gordon 2019). Both metrics are useful in describing anthropogenic sounds, and we analyzed both in relation to grouse trends.

It is important to note that both L_{A50} and L_{Aeq}, when measured before a proposed development, are almost certainly influenced to some degree by sounds of human activities such as ranching and farming, as well as aircraft, vehicles, and railroads. Wyoming executive order 2019-3 is specific on the L_{A50} metric and its use in assessing the effect of noise, stating that "sound levels at leks, due to new project noise individually or cumulatively from anthropogenic sources, should not exceed 10 decibels (dB) above baseline at the perimeter of the lek" (Gordon 2019). In other words, the L_{A50} used to assess acoustic effects must be a cumulative L_{A50} of all anthropogenic sounds, including both noise due to a new project plus that due to other current human activities, and not just the L_{A50} of the proposed new activity.

The *background sound level* is an important metric because it is the background level against which anthropogenic sounds are compared and monitored after a project has begun. The *existing sound level* is important because it is used to measure post-development sound levels, and it is used to determine if post-development sound levels exceed levels detrimental to the species of interest. Many current grouse-management policies state that projects' sound levels plus sounds of other human activities shall not exceed background sound levels (L_{A90}) by 10 dB, as measured at the perimeter of the lek (see NDOW 2018, Gordon 2019). It is critical that both variables be measured correctly and consistently, and the only way to ensure this is to establish standards for equipment, measurement protocols, analysis, and reporting (see below).

Definitions of additional terms can be found in Barber et al. (2011) and Pater et al. (1999). *Audibility* is the ability of animals with normal hearing, including humans, to hear a given sound. Audibility is affected by the animal's intrinsic ability, other simultaneous interfering sounds or stimuli, and by the frequency and amplitude of the sound. *Frequency weighting* is used to adjust the amplitude of various parts of the frequency spectrum for specific purposes. A-weighting (dBA) is used to account for differences in the sensitivity of human hearing as a function of frequency. A-weighting de-emphasizes low

(<500 Hz) and high (>6000 Hz) frequencies while emphasizing those in between, in an effort to simulate the response of human hearing. The *noise floor* (*instrument self-noise*) is the inherent electrical noise of all components of a sound-level meter (meter, microphone, and preamplifier), and is generally considered, although not entirely accurately, as the device's lower measurement limit. The *background noise level* is the total acoustical and electrical noise, from all sources in a measurement system that may interfere with the production, transmission, time averaging, measurement, or recording of an acoustical signal. "Background noise" differs from "background sound" in that background noise is typically electrical noise in the measurement system, while background sound is the sound level in a given environment without the specific sound source of interest.

The American National Standards Institute (ANSI) has established accuracy and stability standards for three types of sound-level meters, types 0, 1, and 2. For Type 1 meters, the maximum change within one hour of operation is 0.3 dB; for Type 0, 0.2 dB; for Type 2, 0.5 dB. The maximum allowable deviation varies by frequency, with lower frequencies having tighter standards, −1.0 dB to +1.5 dB at 31.5–2000 Hz for Type 1 meters. Type 0 meters allow for roughly half this deviation, and Type 2 meters allow for roughly twice this deviation. Type 1 sound-level meters are generally used for environmental studies, although for some situations, such as long-term monitoring, Type 2 standards may be adequate.

Sound-Level Measurements

To establish background sound levels, we collected "reference" data at six locations in undeveloped sagebrush, generally 0.3–1.0 m high, and >5 km from development. The reference measurements were made in April, the primary month of sage-grouse lekking in central Wyoming, of 2013 and 2014, with a an average of 19 days per site. The sites were selected in conjunction with Wyoming Game and Fish Department biologists. Three were within 150 m of leks and three were not near leks. We set a goal of at least 14 days of measurement to account for natural variability in acoustic conditions and to ensure reported levels are ±3 dBA of levels typical for the season and location. We selected this interval after considering several multiyear sets of data from national parks (Iyer 2005), but the topic needs more study. At one site, Bates/Shirley Hole, the weather restricted us to 13 days of measurements.

In the Pinedale gas field, we measured sound levels at 37 locations. Of these 37, 20 were near leks and 17 were near specific gas-field operations. The 17 measurements near gas-field operations were taken in April 2013, with an average of 1.4 days per site. As the sounds generated in gas fields tend to be consistent, varying little from day to day or year to year, these sites did not require measurement over so long an interval as measurements at leks. Measurements at the 20 leks, all during April, extended over the 8-year period 2013–2020, with an average of 5.2 days per lek per year. This 8-year interval is shorter than the period over which grouse were counted at the leks (2000–2020), and this could introduce unexplained variation into our analysis. However, we chose to use the longer interval for calculation of trends rather than restricting our calculations to 2013–2020 for two reasons.

First, the gas field has been in operation essentially from 2000 onward. There were only three well pads prior to 2000, and the majority of development was from 2001 to 2005. Relatively few additional well pads have been constructed since 2006 (we were unable to obtain information on the number of pads constructed per year from the companies operating them, and relied on Google Earth imagery for these observations). Since 2005, the distance between most leks and the nearest well pad has changed little. The distance from one lek to the nearest well pad decreased by roughly 50%, and, assuming an increase of 6 dB per halving of distance (or a decrease of 6 dB per doubling of distance, see OSHA 2013), we estimated that sound levels at this lek increased by 6 dB. Second, although seven of the leks in our study area were abandoned before 2013, excluding these leks would remove from our analysis those leks that may have been most strongly affected by development. For our analysis, therefore, we assumed that sound levels at leks from 2013 to 2020 were representative of sound levels following the initial period of development (2001–2005), except at the one lek where we estimated that the sound level increased by 6 dB. Overall, annual variation in sound levels for the period 2013–2020 was small: the mean standard deviation in L_{A50} was 2.2 dB (range 0.8–4.1). At the seven leks abandoned before our acoustic study began in 2013, we estimated sound levels from the averages during our first two years of measurements. At the leks abandoned during our study, we used data through the last year of occupancy.

Protocols for Measuring and Reporting Sound Levels

Because measurements of sound levels in gas fields could be used as evidence of habitat degradation, they are controversial and open to criticism. Therefore, they should be taken with ANSI Type 1 equipment rated to a sensitivity appropriate for the acoustic conditions of each study area. In this study, we used equipment with a noise floor of 14 dBA, but more sensitive sound-level meters are now available (noise floor 5.5 dBA). The protocol we developed for measuring and reporting sound levels in sagebrush is presented in detail in the Appendix, available at https://archive.westernfieldornithologists.org/archive/V52/Ambrose_Appendix/.

Instrumentation

We used Larson-Davis 831 sound-level meters with PCB 377B20 microphones, Larson-Davis PRM831 preamplifiers, and Larson-Davis EPS2106 environmental shrouds (open-cell foam windscreen and spike to discourage birds from perching on it; Larson-Davis, Provo, UT). Sound-level meters, microphones, preamplifiers, and environmental shrouds met ANSI Type 1 standards. We used Roland R05 digital recorders (Roland, Los Angeles, CA) with Wildtronics Micro Mic PIP microphones (Wildtronics, LLC, Newton Falls, OH) and 90-mm foam windscreens (GRAS Sound and Vibration, Beaverton, OR) to make continuous recordings (16-bit, MP3, 128 kilobytes per second). We placed equipment at the perimeter of leks in sagebrush >0.3 m tall to hide equipment from grouse view and to serve as a windscreen. Microphones were 0.3 m above ground, the average height of a grouse's ear. We used a Bruel & Kjaer 4231 (Bruel & Kjaer, Norcross, GA) field calibrator to check calibration at the beginning and end of each measurement period. All instruments were calibrated according to the manufacturer's standards and schedules. We synchronized all equipment components at the beginning of the measurement period by means of the GPS. Figure 2 shows a typical setup of the equipment.

In 2013 and 2014, we used Young Model 12102 anemometers (R. M. Young Co., Traverse City, MI) connected directly to the LD 831 to record wind speed once per second. Wind blowing on the foam windscreen can influence the sound levels the instruments record. The sound of wind through vegetation is natural, but the sound of wind on the foam windscreen is not. Such "pseudo noise" is usually addressed by excluding data collected when wind speeds exceed 5 m/sec. (ANSI 1994). However, at the 0.3-m height we placed our microphones and in sagebrush >0.3 m, wind speed exceeded 5 m/sec <0.02% of the time. Therefore, the influence of pseudo noise was minimal, and we did not exclude any data from analysis on this basis.

Sound-Level Metrics

Sound-level meters collected continuous 1-second dBA, dBC, and dBF, as well as unweighted one-third octave band levels, 12.5–20,000 Hz, for the entire measurement period. From these 1-second data, we computed 1-hour values for L_{Aeq}, L_{A10}, L_{A50}, L_{A90}, L_{Amin}, and L_{Amax}. Then from these hourly summaries, we computed average (arithmetic mean) sound levels

Figure 2. Typical deployment of equipment for measuring sound levels, showing case holding sound-level meter, digital recorder, and batteries, and microphone (with foam windscreen and spike to discourage birds from perching on it) 0.3 m above ground in sagebrush >0.3 m high.

for all hours of the day (00:00–24:00) as well as for the period during which sage-grouse attend leks (18:00–08:00; all times Mountain Daylight Time). The interval 18:00–08:00 is specified in several guidelines for Greater Sage-Grouse management (NDOW 2018, Gordon 2019). For sites for which we had multiple years of data, we calculated the arithmetic mean of the annual levels for a long-term average. We used the arithmetic mean of all reference sites in undeveloped sagebrush to represent overall levels of background and existing sound for Wyoming.

Influence of Sound-Level Meters' Electrical Self-Noise

The components of sound-level meters produce inherent electrical self-noise, such as that introduced by the microphone, preamplifier, and power supply. When actual sound levels are within 10 dB of a meter's electrical self-noise (noise floor), they are lower than the level the meter reports and should be corrected. The sound-pressure level that a meter displays is actually the addition of two electrical signals: the instrument's electrical self-noise plus the actual environmental sound. Added logarithmically, two sound levels of equal magnitude yield a reading 3 dB greater than the sound level from one of these sources. For example, if the electrical self-noise of a sound-level meter is 13.0 dBA, and the actual sound level is 13.0 dBA, the meter reads 16.0 dBA. When the electrical self-noise of a sound-level meter is well understood, its readings can be corrected for noise-floor influence by decibel subtraction.

While sound levels corrected for self-noise may not meet ANSI Type I standards (specifically, corrected sound levels may not be ±1 dB of actual levels), corrected levels are generally more accurate than uncorrected levels and should be reported when levels are within 10 dB of the instrument's noise floor. Ideally, sound levels should be measured with meters sensitive enough to preclude the need for noise-floor correction; however, if low-noise meters are not available, readings should be corrected for the noise floor. The meters we used in this study had noise floors of 13–15 dBA. At our six reference measurement sites, most values of L_{A50} (69%) and L_{A90} (83%) were within 10 dB of the instruments' noise floor. Hence most of the levels reported by the sound-level meter were higher than actual levels, and thus the need for noise-floor correction.

In 2014, at one of our reference sites, we tested this correction method by comparing 5 days of data collected with a standard ½″ microphone (noise floor 13.0 dBA) with data collected simultaneously by a very low-noise GRAS 1″ microphone (noise floor 0 dBA). Using the known noise floor and decibel subtraction, we corrected levels of the ½″ microphone and compared the three data sets (1-inch microphone, L_{A90} = 14.1 dB; ½″ microphone uncorrected, L_{A90} = 18.7 dB; and ½″ microphone corrected, L_{A90} = 14.4 dB). Given this close agreement between actual and corrected levels, we corrected values for all metrics. We did not correct values to below 0 dBA, although A-weighted sound levels can be less than 0 dBA, the lower limit of human hearing.

Measurements of Sound Levels in Active Gas Fields

We measured the sounds generated by common gas-field activities at 17 locations in the Pinedale gas field, and at four of these we deployed multiple sound-level meters to assess attenuation rates. We followed Mueller's (2002) recommendation to place the meters two source widths away from the source. At a well pad, say 150 m across, sound is typically generated by several simultaneous activities, such as drilling, generators, and vehicles. In this situation, we placed the sound-level meter 300 m from the drill pad (150 m × 2). But because of interference from other nearby sound sources this was not always possible. At four locations, we placed two sound-level meters at different distances from sound sources, and, whenever possible, we doubled the distance between source and each meter to check attenuation rates. Although we often had to measure gas-field noise at different distances, to offer a consistent comparison of sound levels at the same distance, we present values recalculated to represent sound levels at 100 m. At the four locations with two sound-level meters, with the second at double the distance from the source as the first, we found an average attenuation rate of 6.6 dB (range 6–8 dB) per doubling of distance, very close to the expected value (OSHA 2013). We used a Leica LRF 1200 laser rangefinder to measure the distance from sound source to sound-level meter. To determine the distance from a lek to the nearest active well pad, we measured the distance from the centers of each with Google Earth, which offers imagery for several years during our study period.

Audibility and Digital Recordings

The sound level in decibels alone does not allow identification of all sources of sounds. In acoustic studies, it is useful to know the source of common sounds, both natural and non-natural, and the percent time that such sounds are audible (Francis and Barber 2013). For this we listened to a subsample of the audio recorded during the study. At six sites outside the gas field, we listened to 10 seconds of recording every 4 minutes over 2 days. This scheme captures most non-natural transient sounds such as the passage of aircraft and vehicles (Ambrose unpubl. data). The 10-second/4 minute scheme resulted in a 1-hour recording for each day sampled. All sound sources were logged into a spreadsheet from which we computed audibility. We selected two days randomly at each site, excluding days of inclement weather or strong wind, in accordance with the lek-count protocol. We did not assess audibility at sites in the gas field because the sounds it produces were audible 100% of the time at most locations. At occupied leks outside the gas field, we logged the sounds of displaying grouse during each 10-second segment to ascertain the daily cycle of display.

We randomly selected the days for audibility analysis at each lek for one weekday and one weekend day, with the primary purpose of documenting sources of natural and non-natural sounds, and the percent time that each was audible. We did not select these days with respect to grouse displays or to the phase of the moon. We assessed grouse display sounds relative to the phase of the moon by defining phases from first quarter to third quarter as nights with moonlight and phases from third quarter to first quarter as those without. We compared the differences in the percent of samples with grouse sounds relative to nights with and without moonlight with a paired t-test.

Frequency Weighting for the Greater Sage-Grouse

When the effects of anthropogenic sounds on wildlife are assessed, sound levels should be weighted by frequency to match the hearing ability of the target animal as closely as possible (Pater et al. 2009). The hearing abilities of most animals are not well understood, but the hearing of many species of birds is most sensitive in the same range as human hearing is most sensitive, 1–6 kHz (Fay 1988, Beason 2004). Dooling and Popper (2007) suggested that, in the absence of audiograms for the target species, the hearing of most birds is best approximated by A-weighting, and A-weighted levels are likely the best predictor of disturbance from anthropogenic sounds. Therefore, we used A-weighted sound levels in our analysis.

Counts and Trends of Male Greater Sage-Grouse at Leks

Personnel from the Wyoming Game and Fish Department (WGFD) and Bureau of Land Management (BLM) counted male sage-grouse at all known leks in (n = 20) or near (n = 3) the Pinedale gas field annually, following protocols outlined by WGFD's Sage-Grouse Technical Committee (WGFD 2003). Results of counts at satellite leks (defined as a lek with <15 breeding males within 500 m of a larger lek nearby and assumed to represent the same breeding population) were folded into those of the larger lek. We omitted data from one recently discovered lek in the gas field that had only four years of data, so our assessments were based on 22 leks. The reference leks were similar in habitat and topography to those in the gas field but 7–11 km away from it. Some leks have been counted since 1990, but because most development of the gas field and consistent lek counts started in the early 2000s, we calculated trends on the basis of count data from 2000 to 2020. We considered a lek no longer occupied if no grouse were observed at it during the last two count years, consistent with Western Association of Fish and Wildlife Agency standards (WAFWA 2015). We considered a lek to be occupied if grouse were observed in two or more consecutive years.

We used generalized linear regression with a negative binomial distribution (negative binomial regression) to assess trends. Negative binomial regression is commonly used when the dependent variable is a count and zero or missing values are common (Harju et al. 2010). We used the negative binomial regression coefficient and associated P value to establish if lek counts were stable (no significant change, $P > 0.05$) or increasing or decreasing significantly ($P < 0.05$).

Statistical Analysis

When a new gas well is drilled, its effects on the grouse may include habitat loss, new access roads, vehicle traffic, human activity, noise, light pollution, visible structures, dust, and an increase of predators. Many of these factors are strongly correlated, and we could not single out the contribution of any one variable. For analysis of the relationship between trends in grouse numbers and sound levels at leks, we used Pearson's product moment correlation (r). To identify sound-level thresholds above which trends tend to decline, we used two-segment piecewise regression (Toms and Lesperance 2003, Ficetola and Denoël 2009). For each piecewise regression, we also calculated the R^2, which quantifies how much variability in the response variable is explained by the model, as well as the standard error around each threshold. For these analyses, we used SigmaStat (San Jose, CA) and NCSS 12 (Kaysville, UT).

RESULTS

Sound Levels in Sagebrush Habitats in Rural Wyoming, 2013–2014

We collected 2805 hours of acoustic data at the six reference sites. Mean sound levels for all sites and all hours combined, corrected for the noise floor, were L_{Aeq} = 26 dB (range 22–30 dB), L_{A10} = 27 dB (range 23–32 dB), L_{A50} = 19 dB (range 15–24 dB), and L_{A90} = 14 dB (range 10–19 dB). Mean sound levels, corrected for the noise floor, from 18:00 to 08:00, were L_{Aeq} = 24 dB (range 18–28 dB), L_{A10} = 16 dB (range 11–21 dB), L_{A50} = 11 dB (range 7–16 dB), and L_{A90} = 8 dB (range 4–12 dB).

Sound Sources in Sagebrush, 2013–2014

In rural, undeveloped Wyoming, natural sounds were audible on average 71% of the time. The most common were wind through vegetation (49%), birds (35%), insects (8%), rain (2%), and mammals (1%). Non-natural sound sources were less common, audible, on average, 36% of the time. The most common non-natural sounds were jet aircraft (10%), propeller aircraft (4%), vehicles (11%), and unidentified motor sounds (12%). Sounds were not audible 13% of the time.

We analyzed 792 hours of digital recordings at 17 leks for display sounds of Greater Sage-Grouse. These included not only four leks in our study area in Wyoming but also seven observed in similar studies in northern Nevada and six in northern Utah (Ambrose unpubl. data). For all hours (00:00–24:00), 15.0% of the samples had grouse sounds; for daytime hours (08:00–18:00), 2.7% of the samples had grouse sounds; and for nighttime hours (18:00–08:00), 23.8% of the samples had grouse sounds. Of all display sounds, 92.5% were recorded from 18:00 to 08:00, and 45.3% were recorded from 04:00 to 08:00. During this 04:00–08:00 period, the amplitude of display sounds was considerably higher than at other hours (see Figure 3), suggesting this interval was the most important for display. The 06:00 hour had the highest percentage of display sounds, 50.9%. Grouse displayed during all hours of the night, regardless of the phase of the moon. The percent of samples with display sounds during nights with the moon >50% full did not differ significantly from nights with the moon <50% full (paired t-test, t = 2.26, d.f. = 9, P = 0.62). In Figure 3, the elevated sound levels from 04:00 to 08:00 were due to grouse display sounds.

Sound Levels of Common Gas-Field Activities, 2013

In April 2013, we collected 533 hours of acoustic data on common gas-field activities at 17 locations in the Pinedale gas field; at four of these, we made simultaneous measurements at different distances. We were not able to measure all activities at the same distance, so we modeled L_{A50} from all sources at a distance of 100 m to facilitate comparison. The sound of an active drill rig was the loudest, L_{A50} = 62 dB at 100 m, followed by an injection well facility,

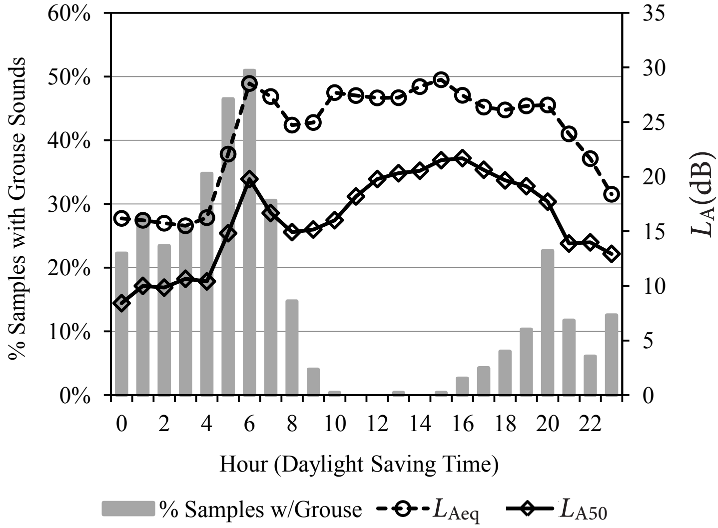

FIGURE 3. Percentage of hours (gray bars) with Greater Sage-Grouse display sounds at 17 leks (4 in Wyoming, 7 in Nevada, 6 in Utah; 1180 total hours), and mean hourly values of L_{A50} (◊) and L_{Aeq} (○), April 2014–2019. Elevated sound levels from 04:00 to 07:00 are due to grouse display sounds.

L_{A50} = 56 dB at 100 m. Sound levels of other gas-field activities were a drill rig being disassembled, L_{A50} = 54 dB at 100 m, compressor stations, L_{A50} = 47–54 dB at 100 m, and a central gathering facility with a generator, L_{A50} = 45 dB at 100 m. At the majority of pads, with active well pumps, sound levels ranged from 32 to 49 dB at 100 m, depending on the number of wells on the pad.

Sound Levels at Leks in the Pinedale Gas Field, 2013–2020

We collected 17,407 hours of acoustic data at 20 leks in the Pinedale gas field. Sound levels varied with distance from the nearest gas-field activity and the type of activity. Sound levels at leks and the distance to the nearest pad were negatively correlated: the closer the lek to a pad, the higher the sound level (L_{A50}: $r = -0.779$, $P < 0.001$). Piecewise regression suggested a breakpoint in the relationship with L_{A50} at 3149 ± 572 m (mean ± S.E, $F = 21.9$, d.f. = 3, $P < 0.001$, $R^2 = 0.785$) and a breakpoint in the relationship with L_{Aeq} at 3117 ± 619 m (mean ± S.E, $F = 16.3$, d.f. = 3, $P < 0.001$, $R^2 = 0.731$). At distances greater than these, sound levels appeared uninfluenced by most gas-field activities (Figure 4), although some loud, relatively short-term activities, such as drilling, could extend this distance. Sound levels at leks were largely dependent on the distance to nearest development or gas-field activity, with sound levels at leks >3200 m from development generally not influenced by anthropogenic sources. For this reason, we distinguish sound-level metrics for leks <3200 m and >3200 m from development (Table 1). Mean sound levels at five leks >3200 m from the nearest pad were L_{Aeq} = 25.2 dB, L_{A50} =

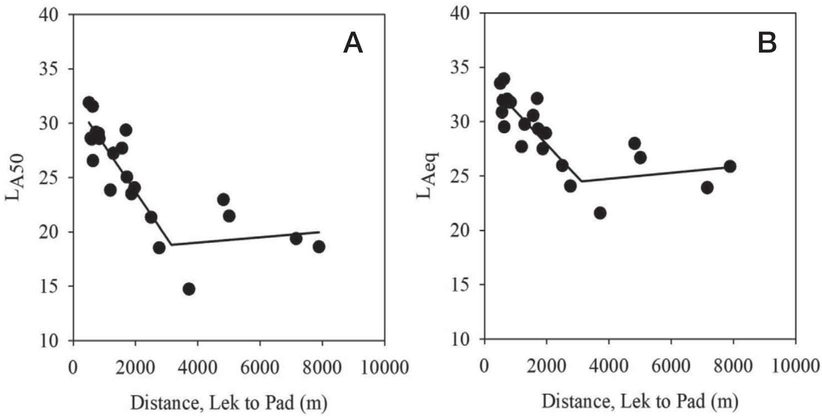

FIGURE 4. Variation in sound levels (A, L_{A50}; B, L_{Aeq}) at Greater Sage-Grouse leks by distance (m) to nearest gas-well pad. At distances >3149 m (L_{A50}) and >3117 m (L_{Aeq}), sound levels were near background levels.

19.4 dB, and L_{A90} = 14.7 dB, similar to background sound levels as measured at the six reference sites (L_{Aeq} = 25.8 dB, L_{A50} = 19.1 dB, and L_{A90} = 14.0 dB). Mean sound levels at 17 leks <3200 m from the nearest pad were L_{Aeq} = 30.1 dB, L_{A50} = 26.7 dB, and L_{A90} = 23.3 dB

At leks far from gas-field activity, sound levels followed the typical daily pattern of being lowest during the evening and early morning and highest during daylight, owing primarily to higher wind speeds during daytime hours (Figure 5, PAPA103). At leks close to gas-field activity, sound levels varied little regardless of the time of day (Figure 5, PAPA001), as active wells run continuously. Over the eight years of measurements, sound levels at leks in the Pinedale gas field varied little (SD = 2.4 dB, range 0.8–4.4 dB) unless activities at nearby pads changed substantially.

TABLE 1 Sound Levels[a] at Greater Sage-Grouse Leks <3200 m and >3200 m from Gas-Field Operations in Wyoming

	Metric			
Distance	L_{Aeq}	L_{A10}	L_{A50}	L_{A90}
<3200 m (n = 17)				
Mean	30.1	31.9	26.7	23.3
Min	24.1	25.2	24.1	14.2
Max	33.9	35.5	31.9	29.4
>3200 m (n = 5)				
Mean	25.2	26.7	19.4	14.7
Min	21.6	22.8	21.6	10.1
Max	28.0	29.0	23.0	19.1

[a]Corrected for noise floor influence.

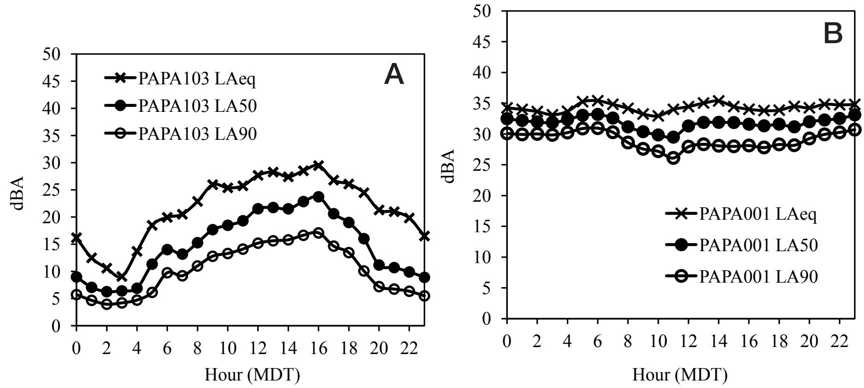

FIGURE 5. Sound levels by hour at a Greater Sage-Grouse lek far (A, 3713 m) from a well pad and at a lek near (B, 502 m) a well pad. ×, L_{Aeq}; ●, L_{A50}; ○, L_{A90}.

Lek Count Trends, 2000–2020

It is difficult to track trends in cyclic species such as sage-grouse unless count data are available for one or more cycles. In the Pinedale area, sage-grouse numbers appear to be roughly on a 10-year cycle (this study), and the difference between high counts and low counts in the cycle can be large, with high-year counts being often more than double low-year counts. With count data for two cycles (21 years), we were able to assess the longer-term trend. At the 22 leks analyzed, seven were occupied during all 21 years of lek counts (2000–2020), eight were abandoned, six were new or newly discovered, and one became occupied, was used for eight years, and then abandoned. At the 19 leks in the gas field with long-term counts, the trend at 12 was declining, at the other seven, stable or increasing (Table 2). At the three reference leks outside the gas field, grouse numbers were stable. While the number of leks occupied annually in the gas field remained relatively stable through our study (mean = 12.8, range 11–15), the total number of male grouse counted annually at these leks declined significantly (Poisson regression, $b = -0.02$, $\chi^2 = 161.5$, $P < 0.001$).

The mean sound levels at the 10 leks where the numbers of grouse were stable or increasing were $L_{A50} = 21.9$ dB and $L_{Aeq} = 26.8$ dB, whereas at the 12 leks where grouse were declining, mean levels were $L_{A50} = 27.8$ dB and $L_{Aeq} = 30.7$ dB (Figure 6). In both metrics, the differences between stable and declining were significant. For L_{A50}: $t = -3.781$, df = 20, $P = 0.001$; for L_{Aeq}: $t = -3.391$, df = 20, $P = 0.003$.

Influence of Gas-Field Sounds on Trends

Our piecewise regression analyses suggest there are thresholds of L_{Aeq} and L_{A50} above which the numbers of Greater Sage-Grouse displaying at a lek tend to decline. For L_{Aeq} the threshold was 31.1 ± 0.6 dB (mean ± S.E, $F = 8.33$,

Table 2 Trends in Greater Sage-Grouse Numbers and Sound Levels at 26 Locations in Wyoming, 2013–2020

				Sound level	
Lek/site[a]	Trend[b]	P	Stable or declining?	L_{Aeq}	L_{A50}
PAPA001	−0.479	0.00	D	34.1	31.6
PAPA002	−0.111	0.05	D	31.3	27.9
PAPA003	0.158	0.00	S	30.6	27.7
PAPA004	−0.003	0.84	S	27.8	23.7
PAPA005	−0.602	0.00	D	30.9	27.4
PAPA006	−0.707	0.00	D	32.2	29.5
PAPA007	−0.049	0.00	D	32.2	29.5
PAPA008	−0.192	0.00	D	32.7	30.5
PAPA009	−0.078	0.00	D	32.3	29.6
PAPA010	−0.225	0.00	D	31.9	29.2
PAPA011	0.074	0.05	S	28.5	23.2
PAPA012	0.013	0.55	S	29.4	25.0
PAPA013	−0.181	0.00	D	32.4	29.6
PAPA014	−0.618	0.00	D	32.4	28.9
PAPA015	−0.249	0.00	D	25.9	20.5
PAPA016	0.049	0.07	S	28.4	23.8
PAPA017	−0.065	0.00	D	28.4	24.5
PAPA018	0.006	0.74	S	26.4	21.5
PAPA019	0.018	0.17	S	26.8	21.6
PAPA025	NA	NA	NA	27.7	22.3
REF101	0.022	0.09	S	23.9	19.4
REF103	−0.021	0.37	S	21.6	14.7
REF104	−0.026	0.68	S	25.9	18.6
REF105	NA	NA	NA	25.4	17.4
REF106	NA	NA	NA	30.1	24.1
REF107	NA	NA	NA	28.1	20.6

[a]One lek with only 4 years of count data not included; 3 reference sites not near leks.
[b]Negative binomial.

d.f. = 3, $P = 0.001$, $R^2 = 0.581$); for L_{A50}, 26.2 ± 1.2 dB ($F = 7.08$, d.f. = 3, $P = 0.002$, $R^2 = 0.541$) (Figure 7).

At the 11 leks with $L_{A50} > 26$ dB, the trend was declining at 10 and stable or increasing at only one (Figure 8). At the 11 leks with $L_{A50} < 26$ dB, the trend at two was declining and at nine was stable or increasing. The mean trend at leks with $L_{A50} < 26$ dB was −0.032, essentially stable ($P = 0.204$), whereas at leks with $L_{A50} > 26$ dB the mean trend was −0.242, a significant decline ($P < 0.001$). At all seven of the leks where $L_{Aeq} > 31$ dB, the trend was declining. Of the other 15 leks where $L_{Aeq} < 31$ dB, the trend was flat at 10 and declining at five. There was considerable overlap in trends by both measures: the mean for leks where $L_{A50} < 26$ dB was −0.032 (range −0.249 to 0.059); for those where $L_{A50} > 26$ it was −0.242 (range −0.707 to 0.1131). At the 15 leks where L_{Aeq} <31 dB, the mean trend was −0.050 (range −0.249 to 0.131); at the 7 where L_{Aeq} >31 dB, it was −0.324 (range −0.707 to −0.051) (Figure 8).

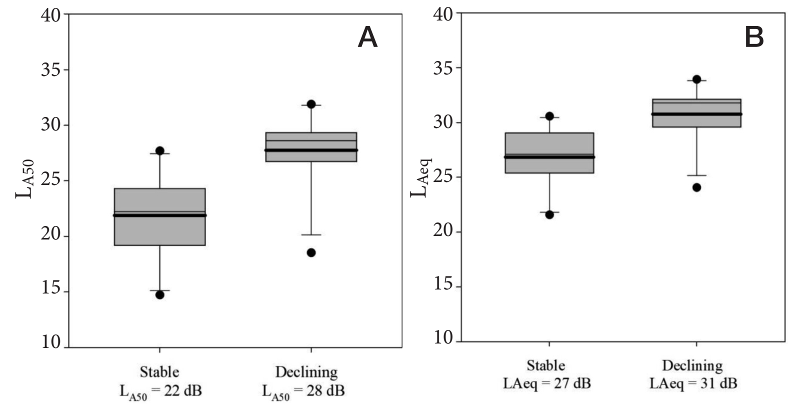

FIGURE 6. Box plots of sound levels (A, L_{A50}; B, L_{Aeq}) at Greater Sage-Grouse leks in and near the Pinedale gas field where numbers of grouse are stable (n = 10) and declining (n = 12). Box represents 75% of data; thick horizontal line; mean, thin horizontal line, median; dots, minimum and maximum levels; whisker marks, 5th and 95th percentiles.

DISCUSSION

Sound Levels in Sagebrush Habitats in Wyoming

Sound levels in undeveloped sagebrush of Wyoming in April were generally low, particularly during the night and early morning when wind speeds were low. Even including low levels of anthropogenic sound, we found these levels were much lower than previously reported (BLM, Pinedale Anticline Project Office, unpubl. reports). This was due to our use of more sensitive equipment and addressing the instrument's electrical self-noise. Daytime

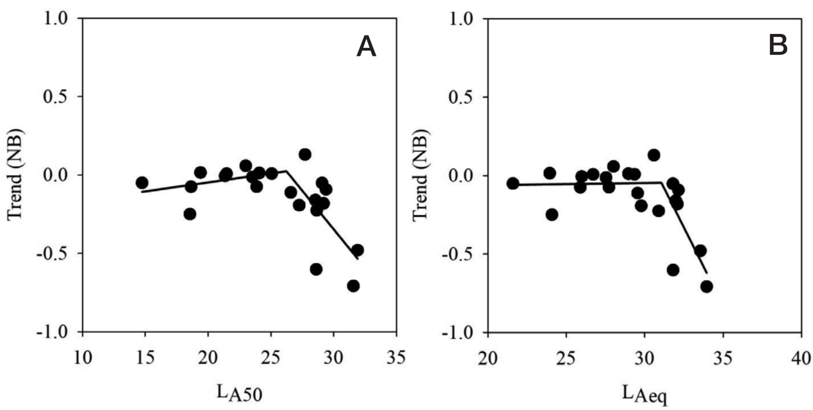

FIGURE 7. Trends (negative binomial) in numbers of Greater Sage-Grouse at 22 leks versus sound levels quantified as L_{A50} (A) and L_{Aeq} (B). Piecewise regression thresholds: L_{A50} = 26.2 dB; L_{Aeq} = 31.1 dB.

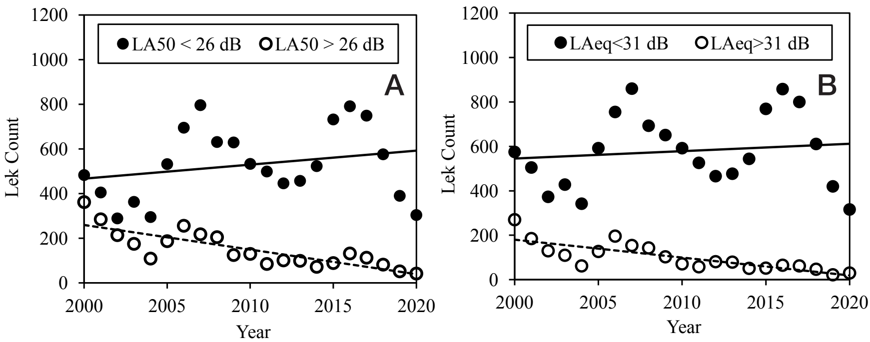

Figure 8. Comparison of annual counts of Greater Sage-Grouse, 2000-2020, at 22 leks in and near the Pinedale gas field with higher and lower measured sound levels. A, L_{A50} < 26 dB (●, n = 11) versus L_{A50} > 26 dB (○, n = 11). B, L_{Aeq} <31 dB (●, n = 15) versus L_{Aeq} >31 dB (○, n = 7). Lines are best-fit linear regression; solid lines, stable trends; dashed lines, declining trends. Declines significant when L_{A50} >26 dB and L_{Aeq} >31 dB (both P < 0.001).

levels were generally 5–10 dBA higher than nighttime levels, primarily because of the sound of wind through vegetation. Anthropogenic sounds, mostly distant aircraft and vehicles, were audible on average 34% of the time, all hours pooled, with little difference between daytime (36%) and nighttime (32%). During some hours, anthropogenic sounds were audible >50% of the time, likely influencing L_{A50} during these hours.

Influence of Grouse Display Sounds on Measured Sound Levels

Gordon (2019) and WGFD (2019) recommended measuring sound levels at the perimeter of the lek, with the goal of assessing increases due to anthropogenic sources. At leks with large numbers of displaying grouse, grouse displays themselves elevate sound levels (Figure 3). One potential solution is to measure sound levels away from the lek but at an equal distance to the nearest anthropogenic source. The appropriate distance from a lek depends on the number of grouse at the lek, as sound levels increase with the number of displaying birds. On the basis of our measurements, we recommend a distance ≥250 m from the perimeter of the lek. Although at this distance grouse are usually audible, the influence of their displays on sound levels is generally minimal. A drawback of this approach is reducing the value of recordings for determining the presence of grouse at a lek. If the primary goal is to quantify sound levels at leks relative to anthropogenic sources, measurements should be made >250 m from the perimeter of the lek. If the primary goal is to study grouse biology, measurements should be made at the perimeter of the lek.

Relationship of Anthropogenic Sounds to Lek-Count Trends

Anthropogenic sounds have a significant effect on trends in counts at Greater Sage-Grouse leks above L_{A50} = 26 dB and L_{Aeq} = 31 dB. Descriptive statistics confirm these relationships: at 11 leks where L_{A50} >26 dB, the trend was declining at all but one; of the 7 leks where L_{Aeq} >31 dB, all were in decline.

The relationships between trends and sound levels were slightly stronger for all 24 hours of the day combined than for hours of lekking (18:00–08:00) only: L_{A50}, all hours: $r = -0.504$, $P = 0.017$ versus 18:00–08:00: $r = -0.488$, $P = 0.021$; L_{Aeq}, all hours: $r = -0.509$, $P = 0.016$ versus 18:00–08:00: $r = -0.479$, $P = 0.024$.

While our analysis demonstrated a significant relationship between trends in grouse numbers and sound levels, we are not suggesting that other aspects of gas-field activity do not contribute to declines in lek attendance as well. For example, we measured the distance from the lek to the nearest well pad in Google Earth and also the percentage of the area within 3 km of the lek that had been disturbed, using imagery from the University of Wyoming's Geographic Information Science Center. Both the distance to nearest well pad and percent area disturbed within 3 km were strongly correlated with trend at the lek ($R^2 = 0.485$, $P = 0.007$ and $R^2 = 0.772$, $P < 0.001$, respectively). The threshold for an effect of well-pad distance was 1560 m and for percent area disturbed was 4.4%. Well-pad distance and percent area disturbed were also correlated with L_{Aeq} ($R^2 = 0.731$, $P < 0.001$ and $R^2 = 0.799$, $P < 0.001$, respectively) and L_{A50} ($R^2 = 0.785$, $P < 0.001$ and $R^2 = 0.841$, $P < 0.001$, respectively). With this high degree of multicollinearity, we could not assess the relative importance of any these variables relative to trend. For several other possible contributing variables, such as number of predators, light pollution, dust, vehicle numbers, and level of activity at each pad, we have no data and could not compare to trend. Some of these factors are likely correlated with sound and may contribute to the relationship between sound levels and declines in lek attendance. Other factors, such as habitat loss to wildfire or conversion to cheat grass (*Bromus tectorum*), have no relationship to sound but have documented adverse effects on Greater Sage-Grouse (Ielmini et al. 2015). In our analyses of well-pad distance and percent area disturbed, we found declining trends at all leks <1560 m from a well pad and 85% of leks with >4.4% area within 3 km of the lek disturbed.

Our analysis implicates anthropogenic sound as a major negative influence on grouse in the Pinedale gas field, and examination of other types of development, even different types of gas-field development, would likely find factors other than anthropogenic sounds detrimental to Greater Sage-Grouse. It is difficult or impossible to assess the relative importance of any factor because of the high degree of multicollinearity among the variables. The ideal way to isolate the effects of various types of disturbance on population declines is to introduce each possible source experimentally in a controlled way. While it is not feasible to experimentally introduce, for example, a large-scale increase in the percentage of area disturbed without also introducing other factors, it is feasible to experimentally introduce sound. In an experimental study of introduced road sounds in Idaho, McClure et al. (2013) observed declines in several species of songbirds and almost complete avoidance by others. Blickley et al. (2012) broadcast gas-field sounds (recorded in the Pinedale field) at otherwise undisturbed leks at another site in Wyoming and found declines in attendance, altered behaviors, and evidence of increased stress in grouse at experimental leks in comparison to control leks. Ware et al. (2015) introduced traffic noise in a roadless area during autumn migration and found that 31% of the bird community avoided the experimental area. Taken together with ours, these studies support the hypothesis that noise alone can depress sage-grouse populations.

Thresholds of Acoustic Effects on Other Species

Barber et al. (2011) reviewed four studies that assessed traffic volumes and distances at which various species are adversely affected by anthropogenic sounds. These four studies did not measure sound levels, but from their data on traffic volume and distance, Barber et al. (2011) calculated sound levels above which the animals were affected. The threshold for frogs in Ontario was L_{Aeq} = 43.6 dB, for grassland birds in Massachusetts L_{Aeq} = 38.3 dB, for woodland birds in the Netherlands L_{Aeq} = 42–52 dB, and for grassland birds in the Netherlands L_{Aeq} = 47 dB. These studies did not investigate background sound levels (L_{A90}), so how these threshold levels compare to background levels is not known. Barber et al. (2011) did not calculate L_{Aeq} over 24 hours by averaging hourly levels as we did but used a 24-hour L_{Aeq}. Our approach followed Plotkin (2001), who recommended the hourly approach to account for hour-to-hour variations. In addition, the activities of many species of wildlife are associated with specific hours of the day, favoring analysis of sound levels on an hourly basis. If we calculated L_{Aeq} as did Barber et al. (2011), the threshold level for the Greater Sage-Grouse would be L_{Aeq} = 36.0 dB, making it one of the species most sensitive in comparison to the others studied.

Management of the Greater Sage-Grouse

Our measurements and analysis suggest that plans for monitoring and management of the Greater Sage-Grouse should consider sound levels directly and not rely solely on other measures such as distance or number of wells per unit area. Sound levels at leks were closely linked to the distance to the nearest pad, the number of pads near a lek, and percent area disturbed near a lek. However, even if the effects of distance, number of pads, or habitat loss are each kept low, a cumulative increase in sound levels at a lek could lead to a decline. Pater et al. (1999) argued that while distance from a sound source is often used as a surrogate for sound disturbance, the use of properly measured sound levels facilitates a more robust analysis of potential adverse effects. Barber et al. (2011) and McKenna et al. (2016) also stressed the need for and importance of properly measured sound levels in understanding and managing acoustic effects on wildlife. Comprehensive management plans should set specific guidelines (or limits) for sound levels at leks in gas fields, in addition to other factors commonly used, such as distance to wells, number of pads, and habitat loss.

Our measurements and analyses also suggest that the current approach to managing the effects of anthropogenic sounds on the Greater Sage-Grouse in Wyoming's executive order 2019-3 (Gordon 2019), which limits anthropogenic sounds (both from a new project individually or cumulatively from other anthropogenic sources) to no more than 10 dB over background sound levels, is appropriate. We found that the WGFD's (2019) protocol is the proper approach to measuring and reporting sound levels at Greater Sage-Grouse leks. We suggest, however, that the location of measurement with respect to a lek should be reconsidered, perhaps moved farther from the lek to reduce the influence of grouse display sounds on overall sound levels (while maintaining an equal distance to the nearest anthropogenic sound source). A standardized approach to data collection and reporting is necessary for the accurate acoustic data essential for managing the effects of noise on the Greater Sage-Grouse.

We found that relationships between sound levels and trends in lek attendance were nearly identical whether the comparison was based on all 24 hours of the day or restricted to the hours of lekking (18:00–08:00). This result suggests that female–chick communication may be as important to the grouse as communication between displaying males and females. Therefore, as a basis for background sound levels, the L_{A90} for all 24 hours of the day may be more appropriate than L_{A90} based on the hours of lekking. Wyoming's executive order 2019-3 (Gordon 2019) defines the interval 1 March–15 May as the "breeding season," and this is when most measurements have been made. However, the full breeding season, from displays at leks through the time when young are independent, is likely equally important. Furthermore, anthropogenic sounds, by inhibiting predator avoidance and flock communication, may have a detrimental effect on sage-grouse year round. We recommend that plans for managing the Greater Sage-Grouse include acoustic protections for the entire breeding season and all hours of the day, and that study of potential effects during the nonbreeding season be initiated.

Influence of Instrument Noise Floor

In acoustic studies of the Greater Sage-Grouse and other species, reporting sound levels near the detectors' noise floor without acknowledging its influence is misleading, although common. Omission of this issue has led to confusion among federal and state agencies, wildlife biologists, industry representatives, and politicians regarding sound levels and sage-grouse management. Further, it risks perpetuating inaccurate data that could lead to inappropriate management. It is essential that researchers report the limitations of their data, and it is important that Greater Sage-Grouse managers understand such limitations.

CONCLUSION

There is strong evidence that Greater Sage-Grouse are sensitive to many forms of human disturbance (Naugle et al. 2011, Wisdom et al. 2011), yet the causal mechanisms linking disturbance to the species' declines are poorly understood (Crawford et al. 2004). Furthermore, relatively little work has been done to uncover potential threshold levels of disturbance above which it has negative effects (but see Harju et al. 2010, Knick et al. 2013). In analyzing sound levels and count trends at leks within and around an active gas field, we found evidence both for the direct effect of anthropogenic sounds as a causal mechanism for declines in sage-grouse counts and for thresholds of sound (L_{Aeq} = 31 dB; L_{A50} = 26 dB) above which the number of grouse displaying at leks decreases. We do not know if the declines associated with high sound levels are due to increased mortality or reduced productivity, or if birds simply leave leks with high sound levels and move to other leks. The threshold of 10 dB over background, which has been used to set noise limits in Wyoming and other states, was based on studies of songbirds (WGFD 2003, Dooling and Popper 2007). Our findings suggest that this criterion is also appropriate for Greater Sage-Grouse in Wyoming, as long as the background level is quantified accurately. Whether this criterion is appropriate for all species remains to be determined. Our findings also suggest that sensitivity to absolute values of sound levels may differ by species. Alternatively, management prescribing a sound level not to exceed L_{Aeq} = 31 dB and L_{A50} = 26 dB could be considered. This approach would eliminate the need for establishing background sound levels, which is often difficult or impossible, but additional study is needed to determine if such thresholds are appropriate in other parts of the sage-grouse's range and for other anthropogenic sound sources.

Our results highlight the challenges to effective management appropriate for the Greater Sage-Grouse and other sensitive species as human activities such as energy development (gas, oil, wind, solar, etc.), recreation, agriculture, and urban expansion encroach further into wild areas. Species vary widely in their responses to anthropogenic sounds, and the Greater Sage-Grouse appears to be on the sensitive end of the spectrum. Our results highlight the need to study a diversity of species and habitats to improve our ability to predict and mitigate the effects of noise on bird populations.

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